Chain Home Radar – A Personal Reminiscence

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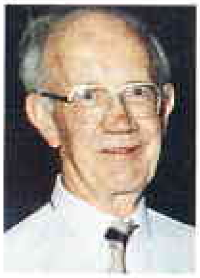


This paper was written to celebrate 50 years in radar. It was begun in October 1992, fifty years after my first awed, ignorant and bewildered introduction to my first radar (an 'A' CH station at Newchurch in Kent) and finished in the spring of 1993, fifty years after my first real radar job as S.T.O. (station technical officer) at Ottercops Moss in Northumberland, an East Coast CH station. My position was immensely privileged, since after a degree in physics I was commissioned directly into the RAF VR: in even the lowest commissioned rank, I had relatively easy access to all classified documents, could mix easily with calibration and quarterly overhaul parties and learn on equal terms from the WAAF officer supervisors, who were highly skilled and experienced in CH operations.

There are good technical accounts of CH radar in the literature, but this paper attempts to give a broader picture, based on personal recollections as well as the technical accounts already noted. CH operation at Ottercops Moss in 1943 cannot have been as hectic or as important as operations at a South Coast station in 1940, yet the stations were virtually identical technically, and the *modus operandi* cannot have changed much either. Therefore it is hoped that this broad-brush account of CH radar will have some interest and value: in a relatively few years, there will be no one left to give a first-hand account.

This paper deals with only one aspect, albeit the most interesting technically and important operationally, of the complete CH (Chain Home) system. The East Coast stations described here were the first to be built and covered the south and east coasts from the Isle of Wight to the Orkneys, with the greatest concentration in S.E. England and the Thames estuary: with their massive free-standing steel towers and their gigantic, complex and horribly inefficient transmitters, they convey something of the urgency underlying their building. For the rest of the country, the same coverage was achieved by the West Coast stations, with much simpler guyed towers and a smaller, simpler and more efficient transmitter. Small gaps in the coverage were finally filled in by a few 'A' (auxiliary) CH stations such as that at Newchurch: this design was similar to that of the mobile stations, one of which, allegedly left behind in France after the Dunkirk evacuation, supposedly led the enemy to believe that he had nothing to fear from British radar.

These CH stations, all working on a wavelength of about 10 metres (30 MHz), were supplemented by CHL (Chain Home Lowflying) stations, which, working at 200 MHz and often sited on cliffs or towers, offset the one great weakness of the 10 m stations, that is, the lack of low cover. There were also GCI (Ground Control Interception) stations, rather similar technically to CHL, but sited inland and designed for the direction of night fighters.

All these ground stations were controlled administratively by Wings which were more or less coterminous with the fighter groups to which the stations reported. Each radar station was autonomous on a day-to-day basis, but Wing H.Q. provided technical services (calibration, quarterly overhauls, etc.) and administrative back-up with such things as pay and personnel services. The whole country was covered by about eight Wings, which in turn reported to the H.Q. 60 Group at Leighton Buzzard. At Ottercops Moss, we reported administratively to H.Q., 73 Wing, which was then at Malton in Yorkshire, and later at Boston Spa. Operationally, we reported to the 13 Group Filter Room at Newcastle.

The Daventry Experiment

The so-called 'Daventry experiment', on 26th February, 1935, has attained the status of folk-lore in British radar history. In the experiment, carried out at Weedon, 6 km SE of Daventry, an RAF bomber at a height of 1800 m flew down the radio beam of the BBC transmitter at Daventry: the transmitter frequency was 50 MHz, and the wavelength therefore comparable with the size of the aircraft. At Weedon, two parallel horizontal wire aerials were erected perpendicular to the beam, and phased together so that the direct signal from the transmitter was almost cancelled out. The small residual signal was received, demodulated and

1 ***The scene is an artist's impression of radar pioneers Wilkins and Watson-Watt about to perform their historic experiment on 26th February 1935.*** ***(courtesy Marconi Radar Systems)***

applied to the Y-plates of a cathode ray tube (CRT), which was itself a rare instrument at the time. The passage of the aircraft modified the signals to the two aerials, causing the CRT spot to move.

The experiment at Weedon, which took less than 24 hours from arrival on site, is portrayed in fig. 1. A. P. Wilkins was one of the four men present, and (one suspects) the architect of the experiment, the other three being A. P. Rowe, R. Watson-Watt (both higher-ranking than Wilkins) and the driver of the grandiloquently-titled travelling laboratory in which the receiver and its display were housed. The scattered signal was detectable even when the aircraft was more than 12km distant, a result which was taken to be very satisfactory.

This account of the Weedon (or Daventry) experiment is based on a little-publicized account by Neale[1], who in turn got it first-hand from Wilkins many years after the event. It was Wilkins who had done the calculations which showed, first, that the idea of a radio 'death-ray' (that is, a ray which would disable or destroy an aircraft) was impracticable, and, second, that the detection of aircraft by some radio-based system might be possible. The Weedon experiment was designed to verify this second set of calculations: unfortunately, there appears to be no record of the calculations themselves.

By 1935, of course, there was abundant evidence that unseen objects scattered incident radio waves sufficiently to be detected. In his initial work on radio waves in the 1880s, Hertz had shown that they were subject to reflection, refraction and interference, just as light was. In a speech in 1922, Marconi commented that:

'I have noticed the effects of reflection of these waves by metallic objects miles away',

and went on to suggest that a ship, suitably equipped, could detect the presence and bearing of other ships. Moreover, in the 1920s, the presence and height of the E and F-layers of the ionosphere had been detected and measured by radio techniques closely analogous to radar. It may be of interest to note that the height of the E-layer is 100km, while the F-layer shows a maximum in the range 200 – 400km. Thus the range of the E-layer corresponds roughly to the minimum radar range useful for early warning (giving 20 – 30 minutes warning of the approaching aircraft at the cruising speeds of the 1930s), while 200 – 400km is the maximum range which might be expected, allowing for the curvature of the Earth, and depending on the height of the aircraft.

All these facts, and others leading to the same conclusion, were well known in 1935. Why then was the experiment needed? Perhaps to convince some bureaucrat who held the purse-strings? Neale suggests that the experiment was needed to verify Wilkins' calculations, which, despite the ionospheric work and the rather casual comments of Marconi, were the only quantitative estimates of what might be possible.

For whatever reason, the experiment was carried out – after all, it cannot have been costly – and the results were received euphorically – Watson-Watt is said to have remarked that Great Britain had once more become an island!

The euphoria is difficult to understand, unless the results indicated a far greater range than the

12 km actually recorded, at which range the target aircraft probably cleared the bottom of the Daventry beam. The aircraft would then have been at 18 km from Daventry, at an angle of elevation of 5 or 6 degrees: the Daventry beam was at 10° elevation, according to Neale, but Baker[2] suggests that such beams were at 15° elevation. The signal-to-noise ratio as the aircraft flew through the peak of the beam was the key result, and must have suggested that the maximum range would be well beyond 12 km. The minimum useful range for an air defence system could be set at, say, 120 km, giving 24 minutes' warning of aircraft approaching at $300\,\mathrm{km\,h^{-1}}$. The radar equation, as such, did not appear until about 1941, but Wilkins' calculations must have shown an R^{-4} term where R is the range to the target, (the transmitter flux falls off as R^{-2}, and the scattered power from the target also falls off as R^{-2} on its way back to the receiver). If the maximum range in the experiment had been only 12 km, an insurmountable gap of 10^4 would have remained between what had been achieved (12 km range) and the minimum useful range of 120 km. It must be assumed that the experiment promised a range of, say, 50 km: this would leave a gap of about 40 times, which it would have been reasonable to expect to fill after some development.

Even supposing the maximum range problem to have been solved by the results, there remained the formidable hurdle that what had been achieved was merely detection, without any hint of how the position or height of an uncooperative aircraft might be found. (In the experiment, the position of the aircraft at any time was known only from the pilot's dead-reckoning). It is not known whether there were already ideas on how the location and height problems might be solved. What is known is that enormous sums of money were immediately granted to cover the development of 'R.D.F.', or radio direction finding, under a 'Most Secret' classification. The title was meant to conceal the fact that it also, and for the first time, covered the location of uncooperative targets.

The Roots of CH Radar

As recounted in Baker's book[2], to which this section is greatly indebted, two developments in radio (or wireless, to use the contemporary name) in the early 1920s had profound and unforeseen effects many years later. The first of these was broadcasting, which led to the growth of radio shops to maintain and repair domestic sets, and to large numbers of amateurs who could build, operate and maintain their own receivers, and even transmitters. This created a civilian pool of skilled radio operators and mechanics, besides those already in the armed services. The Marconi Company was prominent in this development, and the first broadcast station in the UK was the Marconi station 2 MT, transmitting from a wooden hut at Writtle. As Baker[2] recounts, 2 MT was allowed, by a grudging and belated licence, to transmit for half an hour per week (on Tuesdays, 8 – 8.30 p.m.) with a maximum power of 250 W.

The second, more important, development was the use of short waves for long-range communication. It was believed at this time (c.1920) that the way to long range in a wireless link was to use high power and long waves. Indeed, Marconi's Wireless Telegraph Company (abbreviated to M.W.T. Co., a title which lasted until 1963 – here we shall use Marconi) had entered into contracts with the governments of Australia and South Africa to build long-wave high-power stations for communications with the UK: the UK government dithered, being unwilling for such a powerful tool to be in private hands. (As Colonial Secretary, Winston Churchill had a hand in these negotiations). As an indication of the technology at the time, the Australian station was to be of 1 MW power, and the aerial would be supported on 20 steel masts, each 240 m high.

However, in 1923, Marconi himself began a series of experiments between short-wave transmitters at Poldhu in Cornwall and his yacht 'Elettra'. The term 'short wave' here is relative: the initial tests were on a wavelength of 97 m, and further experiments were on wavelengths of 92, 60, 47 and 32 m. The conclusion of these tests was that over long distances, the shorter the wavelength, the greater the range. Accordingly, Marconi's proposed a short wave beam system to the governments involved. These proposals were accepted readily by Australia, South Africa and Canada, and somewhat grudgingly in July 1924 by the UK. The UK contract was so severe in its terms that Marconi made no profit from it: the Company was obviously run by risk-taking engineers rather than by lawyers or accountants. The work was technically, if not financially, successful and links were opened to Canada in 1926, and to Australia, South Africa and India in 1927. At the end of that year, traffic over the four routes averaged over 100 000 words per day, that is, about two and a half issues of the GEC Review.

The Daventry transmitter was, of course, a direct descendant of these short wave beam stations, and the CH system itself incorporated many features first seen there. Thus Franklin invented coaxial cable as a means of distributing power to his beam arrays: in CH, it was used to carry the

receiver signals over 100 m or so from the tops of the receiver towers to the receiver itself. Another innovation was the cooled anode transmitter (CAT) valve, in which the anode of the transmitter valve was a massive water-cooled copper block. This was needed to overcome deficiencies in the glass in valves with glass envelopes: under the influence of heat, high voltages and high RF power, some glass-to-metal seals developed leaks. (An alternative solution, adopted by the British Admiralty, was to use silica envelopes, despite the difficulty of working this material).

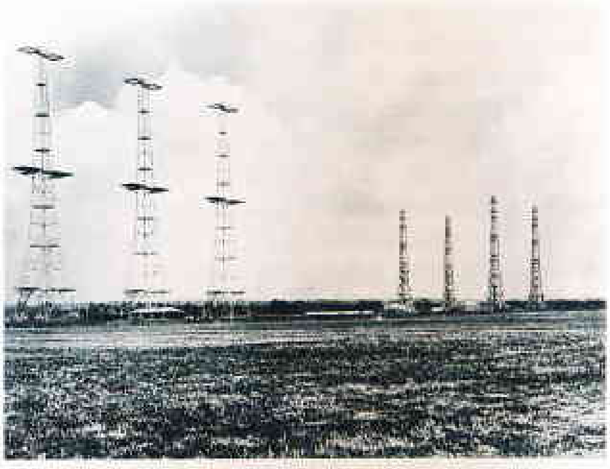
Another 1920s innovation by Marconi which carried over directly into CH was the use of a goniometer (literally, angle measurer) for direction finding. In 1922, Marconi introduced an airborne direction finder, the Type 14 ADF, in which two large orthogonal coils, one running up and down the fuselage of an aircraft, the other across the wings, were connected via a goniometer to a receiver. By tuning in to various radio stations, bearings on them could be taken, and the position of the aircraft established. The goniometer was the key component, since it allowed the use of large coils fixed to the framework of the aircraft. Previously, direction-finding (D/F) stations on the ground used the aircraft's signals to fix its position, which was then radioed to it.

It is clear that well before 1930 many of the key parts of the CH system were in routine use. By 1935, when the query arose after the Daventry experiment 'where to go from here?', it must have seemed natural and safe to develop a system of which so many components were familiar and well-proven. The time-scale was so tight that the less the development needed, the better.

Technical Outline of CH Stations

Neale's paper[(3)], published in 1985 under the editorship of the present author to celebrate the fiftieth anniversary of the birth of British radar (that is, the Daventry experiment), is by far the best overall technical account of a CH station, and should certainly be read, if possible, by those interested. Here only a much shorter account is given; if this leads readers to Neale's account (which may not be easily accessible to some), so much the better. Technical accounts of the transmitter[(4)] and receiver[(5)] have been given in post-war papers by the developers of these components.

The most striking features of an East Coast CH station were the towers: three steel towers, each



2 ***East coast type of Chain Home aerials. 360 ft (110 metre) steel towers at left for transmitting. 240 ft (73 metre) wooden receiver towers at right.***

3 ***A CH transmitter tower, formerly located on the Essex coast at Canewdon, now at the GEC-Marconi Research Centre, Great Baddow.***

110 m high and with three cantilevered platforms on each side (fig. 2) carried the transmitter arrays†, while four 73 m wooden towers carried the receiving arrays. The two sets of towers were

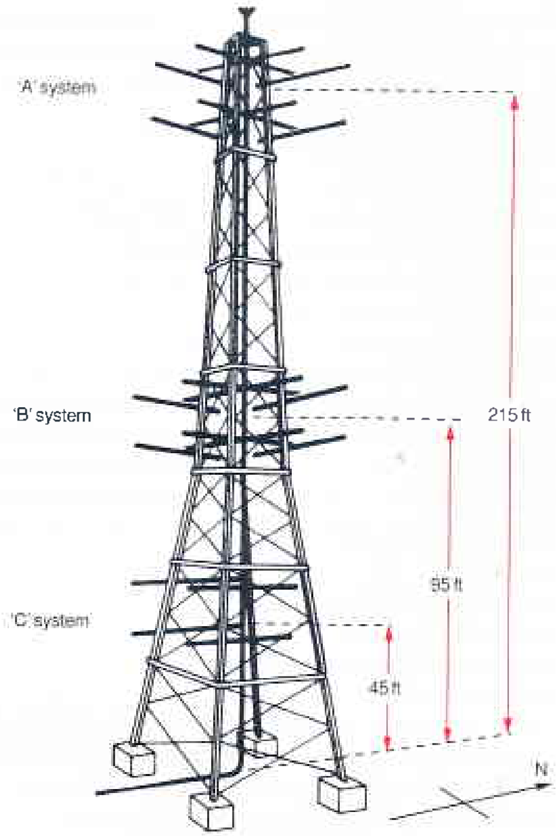
† One of these transmitter towers, perhaps the last to survive, can be seen at the MRC site at Great Baddow and is shown in fig. 3. It was originally installed at Canewdon in Essex, one of the earliest CH stations, and was transferred to its present site in 1959 when the Canewdon station was demolished. The tower is therefore about 55 years old.

perhaps 300 m apart, and each group had a low building, surrounded by an earth-banked anti-blast wall, near the foot of the towers and housing the two transmitters, in the one case, and the two receivers and the operations room in the other. By comparison with the towers, the buildings were inconspicuous and bomb-proof, except for a direct hit. Even the towers, with their lattice construction, were difficult to damage by bombing or gun-fire from the air.

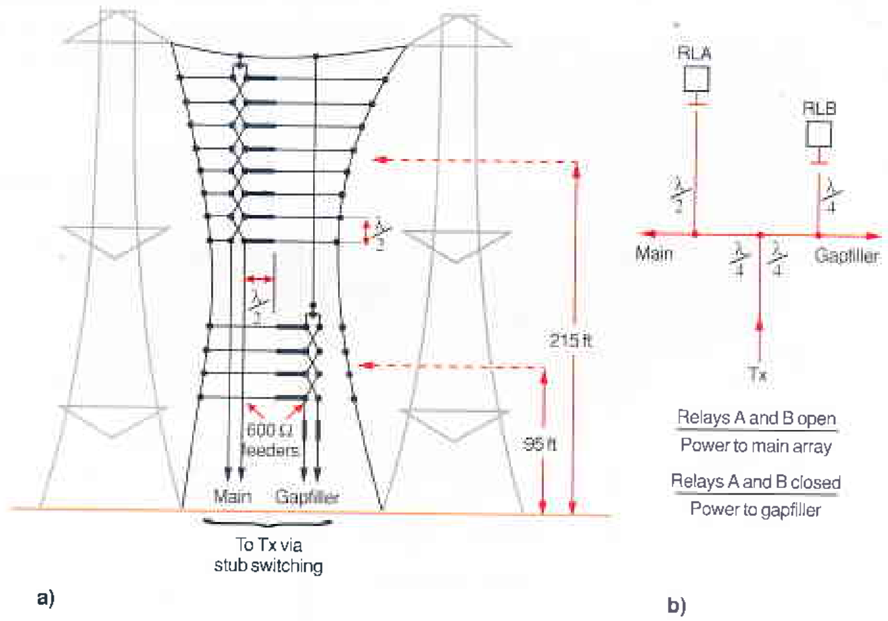
The two transmitter arrays comprised a main array (eight horizontal dipoles stacked vertically at $\lambda/2$ intervals to give a mean height of 65.5 m) and a gap-filling array of four dipoles at a mean height of 29 m: each dipole was backed by a reflector. The power from either transmitter could be switched to either array, and between the main arrays and the gap-filler in either case. The complete transmitter array system is shown in fig. 4, based on Neale's fig. 3.

The receiving aerial systems were three in number, denoted 'A', 'B' & 'C' (fig. 5, based on Neale's fig. 8). The 'A' system, at a mean height of 66 m, consisted of two pairs of crossed dipoles, with two pairs of 'sense' dipoles: the 'B' system, at a mean height of 31 m, was similar, but the 'C' system, at a mean height of 13.7 m, had only a pair of stacked dipoles with fixed reflectors.

In the horizontal plane, the transmitter beam was 100° wide, centred on the so-called 'line of shoot'. In the vertical plane the coverage was determined by the ground reflection pattern. As the lowliest CH operator soon learnt, an array of dipoles at a mean height of h feet gives a ground reflection pattern, with a first lobe at $47\lambda/h°$, λ being the wavelength in metres, a gap at $95\lambda/h°$, a second lobe at $141\lambda/h°$ and so on. These formulae, and their proof, were a standard part of a CH operator's trade test, by which she (operators were usually



5 *Dipole arrays on a receiver tower*



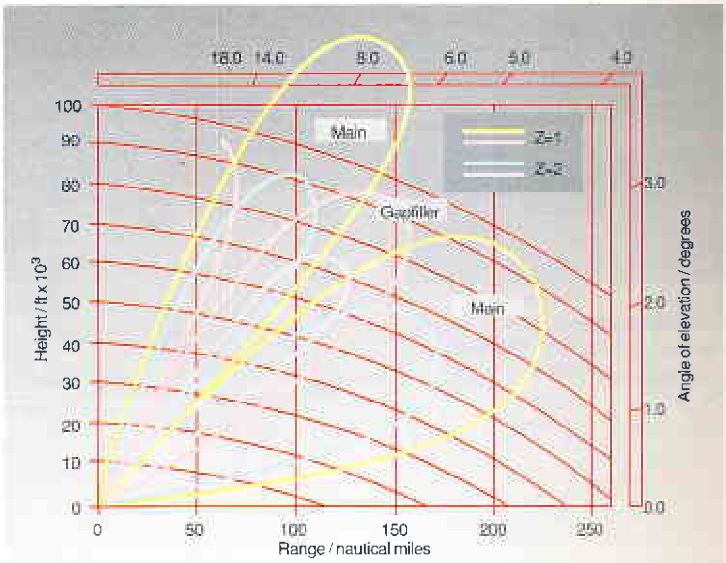
4 *a) CH transmitter array, and b) stub switching*

WAAFs) might progress in pay and prospects. The phenomenon involved is exactly analogous to Lloyd's mirror in optics. In purely metric terms (h and λ in metres), the first lobe is at $14.3\lambda/h^{\circ}$, the first gap at $28.6\lambda/h^{\circ}$, and the second lobe at $42.9\lambda/h^{\circ}$. As applied to CH, λ taken to be 10 m, the formulae give lobes at 2.2° and 6.6° with a gap at 4.4°, for the main transmitter array and the 'A' receiving system. For the gapfiller array and the 'B' receiving system, there are lobes at 4.9° and 14.7°, and a gap at 9.8°. This pattern of lobes and gaps forms the vertical polar diagram (V.P.D.) as shown in fig. 6, which is reproduced from Neale's fig. 6. Of course, this is a theoretical diagram, and assumes that the reflecting ground in front of the arrays is flat, smooth and highly conducting. If these conditions are not met (as they never are completely), then calibration will be needed, and was in fact always carried out, however good the site might appear to be. Further discussion of the V.P.D. will be deferred until the operating procedure of the station is described. Incidentally, Neale's assertion that the pre-war siting instructions laid down that chosen sites must not 'gravely interfere with grouse-shooting' is, I think, apocryphal: at least two thirds of the 22 East Coast stations, and all the most important stations operationally, were well away from traditional grouse-shooting areas.

The East Coast CH transmitter, type T.3026, has been fully described by its designers[4], and more briefly by Neale[3]. The transmitter hall contained two transmitters, each consisting of two large cabinets and a control console fig. 7. The transmitters, although based on a design for a short-wave beam transmitter, needed extensive modification for radar purposes: in particular, in order to generate a well-shaped pulse, the transmitter must be turned on and off quickly at the required times, and the power radiated between pulses must be low when compared with the receiver sensitivity. These were formidable and unfamiliar problems at the time.

Several features of these transmitters are worthy of special note. The RF power was generated in a master oscillator at half the operating frequency, then amplified and doubled in frequency in a driver stage, then amplified to full power by a pair of tetrodes in push-pull. The driver and the two output valves were water-cooled and demountable, continuously evacuated by oil-vapour vacuum pumps, backed by mechanical rotary pumps. These three valves were CATs (cooled anode transmitter), the anodes being so heavy as to

7 ***East coast CH transmitter room***



6 ***Typical theoretical CH performance represented by a vertical polar diagram (V.P.D.)***

require a chain and pulley for lifting. The purpose of this elaborate cooling, pumping and lifting system was to allow the valve filament to be replaced. The filament began life as a thick (5 mm?) hair-pin of thoriated tungsten, 30 cm long, and ended its life when it became so thin as to fracture under the inevitable vibration. The power consumed by these filaments was enormous: 2.6 kW for the driver, 5.5 kW for each output valve. Since even the standby transmitter ran with its filaments hot, the total filament power for the six main valves alone was over 27 kW, as compared with the mean RF power output of about 200 W (25 pulses per second, 16 μs pulse width and a peak RF power of 500 kW). When all the other power supplies are added in, together with power for vacuum pumps, water pumps and blowers, it will be appreciated that the overall efficiency (that is, the ratio of mean RF output to mains input power) was only about 0.5%.

Replacing a filament was a lengthy and error-fraught procedure, which I went through only once: fortunately, my C.O. at the time was an experienced CH engineer, who had done this job before. The valve was allowed to cool, the pumps switched off and the anode lifted against its weight and the atmospheric pressure acting on it. With the anode removed, the screen and control grids could also be removed and the new filament bolted in place: finally, the grids and anode were replaced and the vacuum pumps restarted. Absolute cleanliness was essential, since the grease from a single finger mark would delay final evacuation for hours, besides leading to the suspicion of a leak: the preferred cleaning agent was ether. The final vacuum seal was between machined metal surfaces, and the anode must be lowered exactly in place and square to its mating surface: needless to say, any grit or lint between these surfaces was fatal to any hopes of an adequate vacuum. Then a ring of 'Apiezon' (the name conceals a neat Greek pun) was added around the anode base seal, the filament and grids 'conditioned' by heating to high temperatures, and the valve was once more ready to run. Considering the novelty and complexity of the vacuum systems (most vacuum pumps up to and including the 1930s used mercury vapour), the successful replacement of a filament was something of a triumph: fortunately, it was not something to be carried out every week or month.

The CH receiver was comparatively orthodox, apart from its bandwidth: however, the receiver cabinet, perhaps 2 m high by 2 m wide by a metre deep, also contained all the timing and time-base circuits, the CRO and its power supplies, and the goniometer and range switches. It progressed through various stages of increasing complexity: in 1943, the current versions were the R.F. 6, 6A, 7 and 8 (R.F. stood for 'receiver fixed', as distinct from airborne). The circuitry (all thermionic, of course) was arranged on shallow trays, valves above and other components below; the trays were attached to front panels, which might carry switches, meters and controls, and which were attached by their vertical edges to the uprights of the receiver frame. Viewed from the front, these panels formed an unbroken surface. The display, a 33 cm oscilloscope tube, protruded at the left, with its face perhaps a metre from the floor, and sloping at 30° to the horizontal. Thus, the seated observer viewed the tube squarely, with the gonio knob to her left hand and the range knob to her right. Various controls, for example, for switching the transmitter from main beam to gap-filler, or for switching the gonio from direction-finding to height-finding, were operated by push-buttons within easy reach. Also within reach were the bandwidth switch (three bandwidths were available, 500 kHz, 200 kHz and 50 kHz, to conform to the pulse-width in use) and the receiver tuning controls (all three of the RF stages were tunable and the tuning was checked frequently). Since the display CRT was electrostatic, it was relatively easy (at least by comparison with a magnetically-deflected display) to have a very linear and easily-expandable time-base. This was important, especially with manual plotting, when the time-base was aligned as well as possible with a linear scale, from which the operator read off the range of the target.

The time-base was calibrated with range markers generated from a 9.3 kHz crystal oscillator, which gave marker pips at 10 mile (16 km) intervals. Range accuracy was of considerable importance in the CH system, since despite the undoubted skills of the operators, bearing accuracy was unreliable on very small echoes at extreme range. However, if the same target was picked up by two or more stations, the filter room could often take a 'range cut' on the various plots and so establish the position of the target with some accuracy. In any case, of course, early warning was more important than extreme accuracy: the accuracy of position-finding, even from a single station, would improve as the target grew closer and the signal strength increased.

The signals received on the dipole arrays at the top of the tower were fed, via at least 100 m of coaxial cable, to the stators of the goniometer, picked up by the rotor and transferred via slip-rings to the receiver input: inevitably there were severe losses along this path, losses which might seem at first sight to invalidate the whole system. However, the loss in signal-to-noise ratio would be much lower, because of the very high level of galactic noise present at 30 MHz. Assuming a

galactic level of, say, 3000K at 30MHz and a receiver noise factor of 3dB (= 300K), then a signal-to-noise ratio of ten, say, at the dipoles will be maintained through the cable and the gonio, but the levels of both signal and noise will have been reduced by the losses of, say, 10dB. The total noise at the receiver will be 600K, and the signal will be one tenth of its level at the dipoles: the signal-to-noise ratio through the receiver is now five, that is, a loss of 10dB has only reduced the signal-to-noise ratio by 3dB (from ten to five).

The very rapid increase in galactic noise with increasing wavelength, especially as the wavelength exceeds one metre, favours the lower frequencies, when there are severe losses between aerial and receiver, and may have been one reason for choosing 30MHz, as compared, say, with 60MHz, the frequency of the Daventry experiment. In any microwave radar system, a loss of 10dB between the antenna terminals and the receiver input would be catastrophic, and every effort would be made to avoid losses of even a fraction of a dB.

The receiver room of a CH station was also the operations room, where the raw data measured by the CRT operator were converted into the position and height of the target. The raw data consisted of the range, and two gonio readings, one for bearing, the second for height. These were converted into position and height either manually or by an electro-mechanical calculator, the so-called 'fruit machine', which was based on banks of uni-selector switches, as found in Strowger telephone exchanges. These machines were cared for by ex-GPO personnel, usually sergeants in the RAF; these gentlemen were a law unto themselves who looked down on the ordinary RAF mechanic and were in turn treated with great deference by station technical officers, nominally their superiors. Of course, both the manual plotting table and the wiring of the Strowger switches were modified to allow for calibration results.

Besides its main complement of towers, transmitters and receivers, as already described, a full East Coast CH station had its so-called 'buried reserve'. This consisted of a pair of small auxiliary towers, and an auxiliary transmitter and receiver, each buried in a deep pit. The buried reserve transmitter was an MB2, much smaller and more orthodox than the main transmitters (for example, all the valves were sealed off in glass envelopes, and the transmitter was air-cooled); its power output was much the same as that of the main transmitters. The receiver was one of the RF series, often one step behind the main receivers in the operations room. The aerials were also smaller and simpler, without the elaborate switching arrangements of the main arrays. The buried reserve system was intended as a last-ditch stop-gap, in case the transmitter hall or the operations room of the main system was knocked out by bombing. The reserve system was periodically run up and checked as a system, but was rarely used operationally because of the duplication in the main system, and because, as it turned out, the main system towers and buildings were difficult to damage from the air.

The Operation of a CH Station

Every CH station worked at least 23 hours a day, day in, day out: an hour a day was normally allowed for maintenance, but this could only be taken by agreement with the filter room, and would be cancelled if an adjacent station were off the air for any reason, or if heavy air activity were expected. A table (in effect, a black list) was published every month, giving every station's unscheduled time off the air, and good reasons were demanded if this exceeded a few minutes.

If a station was fully up to strength, it would have four watches of operators, each of six WAAFs and led by an NCO, and four watches of mechanics, each of three men, two in the transmitter hall, one in the operations room. Ideally, a WAAF officer, a highly experienced and skilled ex-operator, was present on each watch as a supervisor, and a station technical officer and the senior NCO mechanic would be present all day, and on call throughout the 24 hours. Very often, of course, the station was not at full strength, and would be reduced to a three watch system, in which everyone worked a full 24 hours every three days: such a regime could not be sustained for more than a few weeks. Mechanics were in even shorter supply than operators, and a watch would often be reduced to a single mechanic, who would haunt the transmitter hall, accompanied by an operator for safety. Under such circumstances, the daily maintenance routine became something of a scramble.

As an aid to an understanding of CH operations, consider a station whose 'line of shoot' was due east, that is, on a bearing of 90°. The transmitting arrays faced E, of course, and the receiving dipoles of the 'A' and 'B' systems ran N–S and E–W: the 'C' system dipoles, used only for height-finding, lay N–S. The sensing dipoles lay N–S, to determine whether a target was in front of, or behind, the station, and E–W, to sense whether the target was north or south of the station. The coverage of the station was determined solely by the width of the transmitted beam, about 110°: in our example, this would be from 35° to 145°. The receiving arrays, of

course, received signals equally from any direction.

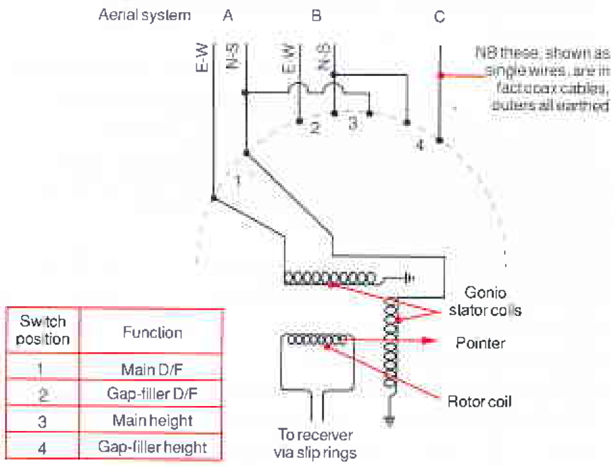
Now envisage the receiving dipoles connected to the goniometer coils as in fig. 8, where the stator coils also run N–S and E–W: in practice, of course, the coils could lie in any direction, with suitable adjustments of the gonio pointer and scale.

A target due east of the station would give a signal only in the N–S dipoles, and this would be transferred to the N–S coils of the goniometer. The goniometer would pick up a maximum signal when its search coil also lay in the N-S direction, and a minimum, (ideally, zero) signal when the search coil lay E–W. Hence, if the gonio pointer is aligned with its search coil, it will point to the east, that is, to the bearing of the target, when the gonio is set for minimum signal. An ambiguity could arise here, since the goniometer would also give a minimum for a target bearing due west, or even when its search coil was 180° from the true bearing. In practice, the ambiguity was resolved by the use of the sensing dipole before any attempt was made to take a bearing.

In the height-finding mode, of course, the gonio measured, not so much an angle, as the ratio between the signals on dipole arrays at different heights: this ratio gives the angle of elevation of the target, and this, combined with the range, gives the height a via simple formula.

The most important operator, by far, was the girl 'on the tube' (fig. 9). It was her duty to update plots on existing tracks at regular intervals, while at the same time watching for new echoes: to this end, the gonio was swung continuously. Since the bearing of a target was determined by swinging the gonio for a minimum (zero) echo, the station was blind on that bearing, or indeed on any bearing on which the gonio rested: hence, the first rule for operators was that the gonio must always be swinging over the full 100° or so of the station coverage. The girl on the tube, together with the others of the team, were paralleled together on the telephone to the plotter in the filter room, who would accept the plots, allocate track numbers (H- for hostile, F- for friendly, X- for unknown), allot priorities ('another plot on X-, please', 'can you get a height on H- ?') and probe for information 'Staxton has a plot about 120 miles from you: can you see anything?' (Staxton being the neighbouring station).

The routine of establishing a new track was quite complex. If the operator noticed a new echo, which would first show as a tiny break in the noise, she would at once 'sense' it to determine that it was in fact in front of the station before announcing 'I have a new echo at such and such a range'. She would then sense again, to determine whether the target was north or south of the 'line of shoot'. She would then attempt, by swinging the gonio for a minimum, to take a bearing, and then a height. On a very small echo, as first picked up, the bearing would probably not be very accurate, and it might



Switch position	Function
1	Main D/F
2	Gap-filler D/F
3	Main height
4	Gap-filler height

8 *Schematic diagram of signal path from aerials to receiver. (Line of shoot is assumed to be due east, orientated as shown in fig. 5, and the gonio is shown for minimum on a target also due east.)*

9 *The 'girl on the tube' responsible for updating plots and watching for new echoes. Her left hand should be operating the goniometer, whose wooden handle is clearly visible. (courtesy the RAF Museum, Hendon)*

be impossible to take a height, since the signal on the lower of the height-finding dipoles would be much smaller than that on the upper, which was itself only just detectable. However, even the range information was valuable as early warning and because it might enable a range cut with an adjacent station: also, knowing the station V.P.D. and the range of pick-up, a skilled operator (or her supervisor) could estimate a height with surprising accuracy. As the target grew closer in range, the signal strength on both upper and lower dipoles would improve, and height measurements and more accurate bearings would become available.

Calibration

The theory of CH direction- and height-finding is simple enough, but depends heavily on the site being ideal. Many sites were obviously far from ideal, and even for those which promised well, it was difficult to be sure about surface slopes and conductivities in the critical areas in which ground reflection occurred. For this reason, CH stations were always calibrated.

Calibration began with a careful check over the receiving system, from dipoles to gonio: in particular, it was important that the feeder runs between pairs of dipoles were of the same electrical length. By injecting signals into the dipoles and adding short lengths of flexible cable in a 'phasing box', equality of electrical length was achieved. The goniometer was also carefully checked for sensitivity and a high cross-talk ratio between the pairs of coils.

Finally, calibration flights were carried out, using either an autogyro (a predecessor of the helicopter) which would hover over local landmarks such as churches, or a small aircraft, which would fly a succession of radial flights at various heights. The position of the target aircraft was often checked with a theodolite. The radar transmitter was not involved in this process, since the aircraft carried a 'squegging' oscillator, which gave an unmistakeable and relatively large signal, which could be 'D/F'd out' relatively easily and accurately by the gonio.

Needless to say, calibration was carried out, not by station personnel, but by a peripatetic band of specialists. While calibration, or re-calibration, was in progress, normal operations were in abeyance, and the station routine disrupted.

Technical Maintenance

At the heart of the RAF system of maintenance for all radar stations (not only CH) was Form 1497, a large pre-printed sheet of paper which on one side carried notes and comments on any repairs or modifications carried out, and on the other side a list, on a day-by-day basis, of the routine maintenance operation which had been carried out. A separate Form 1497 was made out each month for every major piece of equipment (receiver, transmitter etc): the form was clipped like a loose leaf in a book, the covers of which were two pieces of plywood, hinged along one edge and painted black on the outside faces. One side bore a large 'S' (serviceable), the other a large 'U/S' (unserviceable); when the boards were hung in some prominent position on the equipment to which they referred, the serviceability state was immediately obvious to all. Details of the fault (for example, 'no time base') could be looked up on the Form 1497 inside.

Every item of equipment also had a schedule of 'Daily Routine Maintenance' operations. Thus, on Mondays, operations 1, 4, 7, 11 and 15 might be called for on a receiver: for detailed instructions on these, recourse must be had to the handbook, which was of course a secret document. The mechanic would therefore sign out the handbook, carry out the prescribed operations, enter them as completed on F.1497 and return the handbook. In this way and over a period of time, every operation would be carried out, entered on the form and signed for as complete and satisfactory. Over a longer period, the senior N.C.O. mechanic and the station technical officer would also work their way through the routine, either independently or by supervising the mechanic: these tests would also be entered and signed for.

Often, a maintenance operation such as 'clean and inspect the time base panel' would be called for, which seemed to hark back to the maintenance of an aircraft engine. In that case, cleaning might have some point, and inspection might reveal an incipient fault. With a tray holding perhaps a dozen valves with their associated components, inspection was not likely to reveal much; it might detect a loose top cap or a 'soft' valve, but was unlikely to show that a valve was near its end of life, or that there was an incipient dry joint in the panel. While inspection did little harm, if not much good, cleaning did little good, and could do much harm: for instance, a displaced valve might lose contact to one of its pins, causing a difficult and quite unnecessary fault.

Test gear was provided, of course, but the bare minimum to carry out the prescribed tests. Essentially, it consisted of a signal generator and a multimeter: there was no oscilloscope, so that for any out-of-the ordinary fault, for example, in the time-base circuits, recourse must be had to Wing headquarters, perhaps (and very desirably!) a hundred

miles away: there there was an oscilloscope, unless it were already out on a panic call from elsewhere.

Fortunately or not, the perennial shortage of mechanics often meant that only a minimum of tests could be carried out: efforts were then concentrated on those tests and checks which had immediate bearing on the technical health of the station. This was no bad thing, it turned out: a panel thick with dust would carry on quite happily, while attempts to achieve the surgical cleanliness demanded by visiting senior officers did not improve serviceability. Hence the desirability of being far away from Wing H.Q.!

At intervals, nominally every three months, a Quarterly Overhaul party would descend on a station and carry out a complete check of major items: these were teams of two or three engineers, relatively well equipped with test gear, and specializing in receiver or transmitters. These people would carry out a fairly thorough overhaul, extending, for instance, to checking the receiver bandwidths and realigning as required. The transmitter team would check every aspect of the transmitter, including, for instance, the conductivity of the cooling water, which was held in a vast and rather inaccessible tank under the transmitter itself.

Anti-Jamming Provisions

It was clear from the design of a CH station that considerable thought had gone into protecting the system from jamming. Some of these provisions may now be mentioned.

The cathode ray tube itself was specially built to reject transient signals, in favour of target echoes, which would be longer-lasting. This was achieved by using two phosphors in the tube: a blue phosphor excited immediately by the electron beam, and an orange phosphor, excited more slowly by the glow of the blue phosphor. If the tube was observed through an orange filter, transient signals which excited only the blue phosphor were not seen, while the long-lasting echoes were easily visible.

The IFRU (intermediate frequency rejection unit) consisted of a pair of very narrow band rejection filters, which could be tuned separately across the intermediate frequency bandwidth. They were present to reject any accidental or deliberate CW interfering signal.

The AJBO (anti-jamming blackout) circuit was designed to counteract swept frequency jamming. In this very damaging form of jamming, an oscillator is swept in frequency across the pass-band of a receiver, to give a bell-shaped response on the CRT, and completely obliterating any echoes. The AJBO circuit, which worked at video frequency, was designed to discriminate against the slow rise time of the bell-shaped response and blackout the tube: some of the signal time-base would be blacked out and lost, but some would remain, unless the sweep frequency of the jammer was locked to the station PRF (pulse recurrence frequency).

The IJAJ (international jitter, anti-jamming) circuit was designed to introduce a slight random jitter to the PRF of the station, so that jamming pulses triggered by reception of one's own transmitter pulse would not be synchronized with the time-base. Since true echoes would be steady, they could be distinguished from the false pulses from the jammer, which would vary in time from pulse to pulse because of the jitter.

CH stations were also equipped with frequency agility, in that, at least in principle, both the receiver and transmitter could change to any one of four pre-set frequencies in a few seconds under push-button control. In practice, since a need for this facility never became apparent, it was never seriously tested.

Security and Safety

As has been noted above, the Daventry experiment heralded a very large effort towards the implementation of RDF (radio direction finding). The deliberately misleading name was the first of the security measures intended to cover all the developments and their outcome in a cloak of secrecy. Britain was thought to be alone in this field, or, at very least, well ahead of the field. Of course, this was a misapprehension, since as soon as the technology became available, the forecasts (for example, by Marconi himself) of radar were implemented in different ways by almost every advanced industrial nation.

Security, in the sense of preserving secrecy, took various forms. All the documents concerning the system were classified as 'Secret', and elaborate procedures for their destruction in emergency were laid down: for instance, some documents were printed on rice paper, and were to be destroyed in a bucket of acid. Training sessions for operators, and mechanics could be held, but no notes could be taken. A muster of secret documents by an officer from Wing H.Q. was carried out every quarter: this was supposed, impossibly, to account for every page of every document.

Security also extended to control of entry onto the technical site (the living quarters were usually some miles away, and relatively easy of access). The technical site, half a kilometre or more in

diameter, was surrounded by a so-called 'unscalable' steel fence, 2 metres high, in which the only gap was the gate and guard room. Every authenticated visitor, including the watch personnel as they arrived for duty, was given the watchword for the day, without which the doors of the transmitter hall or operations room should not be opened. Of course, this system was a challenge to some senior visitors, who were wont to try to bluff their way in by announcing themselves by their (very senior) rank, or as 'G.P.O.'. A particular offender in this respect was the Senior Technical Officer, one Wing Commander Scott-Taggart, who had achieved considerable fame in the 1920s by designing DIY domestic receivers under titles such as the JS–T1 (a one valve receiver), JS–T2 etc. If he succeeded in bluffing his way in, the door-opener (usually the most junior of the watch) was invariably put on a charge. He felt justified in these tactics, no doubt, by the need to emphasize security, but it did not take long for the news to get around and for the doors to remain firmly shut unless the password was given.

Inside the 'unscalable' fence, each building was protected by a barbed wire apron about 3 m high and thick, complete except for a narrow access gap. Early in 1943, after the Brüneval raid on a German 'Würzburg' radar station, concern was felt about a possible reprisal raid on a British station. Accordingly, some men (including the author) were sent on courses of weapon training etc., by which it was hoped that a station could hold out for an hour or two, until help could arrive. This was a ridiculous hope, as was proved in a night exercise when a half dozen of us, opposed by the alerted military might of the station, penetrated to the door of the operations room without detection. A dozen paratroopers, operating without warning, would certainly have done much more.

By far the most serious risk to the safety of personnel was that of electrical shock. To guard against this, all dangerous areas were closed off by doors, the keys of which must be withdrawn and used to enable the equipment in question to be switched on. Needless to say, this precaution proved too onerous in practice: after all, the equipment must be accessible and switched on if faults were to be found. Therefore, dummy keys were always available, presumably, since the keys were of an unusual pattern, with the connivance of the authorities. The transmitter was of course the main danger, and in particular, the main EHT smoothing condenser; at 2 μF, and charged to its working voltage of 35 kV, this demanded the utmost respect, and was provided with its own 'earthing stick', that is, a metal chain, earthed at one end. The other end, held on a long insulating wand, could be held to touch danger points, so connecting them to earth.

The only other serious danger was in climbing the towers, especially the transmitter towers. This had to be done from time to time as part of routine maintenance; although it could be an unpleasant task, accomplished without a safety belt, no serious accidents were ever reported to my knowledge. In the gales and mists of Ottercops Moss (the site was 300 m above sea level), one climbed slowly and held on very tightly!

Training for Radar

Formal training for technical officers destined for service in ground radar took place at a 14-week course at one or other of the RAF's wireless schools. The course covered all ground radar (CHL and GCI, as well as CH) and was very intensive – eight hours a day, six days a week. There were formal lectures on the theory of the system, and on the operation of each unusual circuit, for example, the time-base. These were supplemented by practical sessions of familiarization with the layout of the equipment, and of fault finding: here the instructor would simulate a fault and the trainees be expected to diagnose it. Here also we learnt the distilled wisdom of the experienced serviceman: 'always keep one hand in your pocket', 'resistors go open-circuit, capacitors go short-circuit', and so on.

It could not be expected that everything would be covered, and the main CH transmitter (the T.3026) was left out, although the much less complex mobile transmitter was included. Such omissions were no doubt necessary and carefully calculated, but it was disconcerting to arrive at Ottercops Moss never having seen the transmitters. Fortunately, I was privileged in having access to the handbooks, and in being able to haunt the quarterly overhaul party.

Radar mechanics were poorly served on the whole: if they arrived at a station with unfamiliar equipment, there was much less time or opportunity for them to learn. Since they were so few and their work more technical than that of the operators, there was no formal training on the station as there was for operators. The unfortunate mechanic must pick up what he could from the maintenance manual, and from watching those with more experience.

Operators, on the other hand, were well cared for: if on a four-watch system, there was some 'free' time, and this was used for training by a WAAF supervisor or senior NCO, or on occasion by the technical officer. The theory was of course much simpler than for a mechanic, and could be taught

without classified documents: nevertheless, no notes could be taken. Regular trade tests were held, so that it was possible to progress by two or three stages relatively quickly. Alas, no such easy progression was available to mechanics.

Conclusions

At first sight, the CH radar would not promise to be a very effective system. The PRF was very low at 25 p.p.s, giving a non-ambiguous range of about 6000km: under 'anaprop' (anomalous propagation) conditions, even this PRF proved too high, and returns from one pulse appeared on the next time-base. This phenomenon, aided by modern data processing, is the basis of over-the-horizon radars: in CH, the nuisance was overcome by halving the PRF to 12.5 p.p.s. As a result of the low PRF, the mean power was also low (200 W at 25 p.p.s., only 100W at 12.5 p.p.s). At 30MHz, the galactic noise level is very high, but as explained above, this was not as serious as it might appear, given the high losses between dipoles and receiver. The aerial gains were also low: 8 or 9dB for the main transmitter array, perhaps 3 or 4dB for the receiving arrays. However, the saving grace of the system was that it was a floodlit system, which meant that 25 pulses were received from every target within the coverage in every second, save for the brief intervals when the gonio passed the bearing of a target: the mean strike rate was therefore at least 10^3 per minute. A rotating beam radar, on the other hand, would put ten to twenty pulses on the target in every revolution, which would take 10 – 15 seconds: the mean strike rate was at most about 100 per minute, moreover, returns from successive revolutions would be completely uncorrelated. One concludes that CH was designed not so much by theory as by a series of careful step-by-step experiments.

Whether by awe-inspiring foresight, or merely by serendipity, the CH radar system, for all its shortcomings, proved a most valuable factor in the air war over southern England in 1940. The battle was fought as dictated by the enemy, an assault by massed aircraft flying at considerable height in daylight. These were ideal conditions for a defence guided by CH, which gave early warning of high flying aircraft, together with a sufficiently accurate indication of position and height for the defence to be deployed in good time and in commensurate strength. Another great strength of the system was the fact that all the stations in a given sector reported to one filter room, which therefore had an overview of the complete picture: it did not matter too much if a single station was out of action for any reason. If the enemy, having monitored the radar transmissions and measured the heights of the towers (the towers at Dover were plainly visible from across the channel) had appreciated the lack of low cover and attacked much nearer sea level, or had expended more effort on jamming the stations instead of trying to destroy them by bombing, the outcome might have been very different.

It is perhaps worth recalling that the commanders on both sides were veterans of the air battles of 1914 – 18, where superior height was generally decisive. The British were therefore content with the cover given by CH; the enemy, for his part, even if he appreciated that CH could not give low cover, evidently decided that superior height was too valuable an asset to be sacrificed, even if this meant early detection. They probably underestimated, not so much an individual CH station, but the integrated and centralized defence system in which detection, plotting and height-finding by CH was only the first, if vitally important, step.

Acknowledgements

This account relies heavily and gratefully on Bruce Neale's 1985 paper on CH and on Bill Baker's 'History of the Marconi Company': I count it a privilege to have known and worked with both these authors. The CH people I knew in 1943 also contributed greatly, by a process almost of osmosis, to my knowledge: alas, they are too numerous to mention, and I have completely lost touch with them.

If it is true, as has been alleged, that all old radar people suffer from nostalgia, it is above all true about CH people. Just as a steam train enthusiast despises diesels, so CH people tend to look down on later radars, however efficient or effective. If this paper helps to foster and preserve that nostalgia, it will have served its purpose.

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